Eating, drinking, living, dying and decaying soft robots

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Soft robotics opens up a whole range of possibilities that go far beyond conventional rigid and electromagnetic robotics. New smart materials and new design and modelling methodologies mean we can start to replicate the operations and functionalities of biological organisms, most of which exploit softness as a critical component. These range from mechanical responses, actuation principles and sensing capabilities. Additionally, the homeostatic operations of organisms can be exploited in their robotic counterparts. We can, in effect, start to make robotic organisms, rather than just robots. Important new capabilities include the fabrication of robots from soft bio-polymers, the ability to drive the robot from bio-energy scavenged from the environment, and the degradation of the robot at the end of its life. The robot organism therefore becomes an entity that lives, dies, and decays in the environment, just like biological organisms. In this chapter we will examine how soft robotics have the potential to impact upon pressing environmental pollution, protection and remediation concerns.

1. Soft robots in a wasteful world

Modern technology is driving our society ever further from a state of environmental equilibrium. Throughout animal evolution the driving force has, perforce, been to fit in with the environment. As competing species grow in population, or as climates change, animals have adapted to re-establish the status quo. In contrast, since the start of the industrial revolution the drive has been technology advancement and the growth of the human race. The newer information technology and robotics revolutions have taken this to an extreme. Now the advancement of society is precariously out of balance with the environment. Technology has the potential to drastically and negatively affect the environment and yet is more and more dependent on the natural world to deliver crucial resources for its sustenance. It is with these environmental and resource pressures that we can turn to soft robotics to provide novel and timely solutions.

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The pressure on natural resources from technology growth is huge and it is striking how soon the modern world is heading for critical events. Semiconductor components and electronic circuits, for example, use significant quantities of rare and exotic materials (Research and Markets 2016). What happens when these resources dwindle? Another example is the lithium polymer battery, a staple of modern portable electronic devices and the enabler of new home power initiatives and future electric transport systems. Fig. 1 shows the current proportion of world lithium production used for batteries (35% in 2016) and the rapid rise in this value over the last four years (USGS 2016). This is in advance of the full impact of the Tesla Powerwall (Tesla 2016) and Gigafactories which are set to consume massive quantities of lithium. The planetary supply of lithium is finite and these new technologies are putting an increasing demand on the raw material (Vikström et al. 2013). What happens to our tech when lithium resources reach critically low levels? Experts are even starting to talk seriously about 'peak X' where X is almost any naturally occurring chemical, much as we talk about 'peak oil' (Hubbert 1982). When we reach 'peak lithium' we will have to carefully examine how we can sustain the burgeoning robotics revolution.

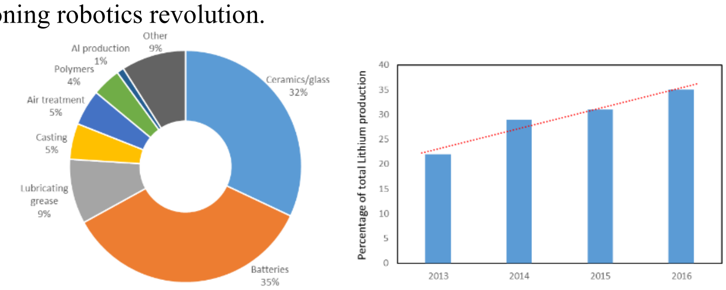

Fig. 1 (Left) Lithium use in 2016, (right) lithium use in batteries 2013-16.

Even more immediate environmental catastrophes are looming which are driven by our rapid industrial, domestic and agricultural development. These include the widespread pollution of our lands and oceans with chemicals, fertilizers and plastics (Schuyler et al. 2014)(Accinelli et al. 2012)(Wagner et al. 2014). These may be result of industrial accidents (chemical release) or farm run-off (nitrate fertilizers). Nitrate run-off is a slow-burn pollution. These chemicals accumulate in the water courses and, when conditions are right, feed the growth of harmful algal blooms. These blooms have multiple deleterious effects: their rapid growth uses up all dissolved oxygen in the water, causing both aquatic flora and fauna to die; and they can release harmful toxins, some of which are extremely dangerous for humans.

The negative effects of the technology described above all have in common a lack of balance with the environment and natural resources. There is a danger with future robotics that we will make the same mistake again, that is, we will develop effective but unsustainable technologies that are out of balance with the environment. We argue that this need not be the case with careful choice and development of sustainable, bio-compatible, environmentally-benign and biodegradable robotics.

Unfortunately, conventional robotics is hampered in this endeavor by the prevalence of toxic and non-biodegradable materials used in their rigid metal and plastic bodies, their silicon processors and their electromagnetic drive systems. In contrast soft robotics offers a new and high-potential set of technologies that can readily be made environmentally neutral and sustainable. In fact, by rethinking the concept of a robot and moving towards a more bio-integrating model of a *soft robotic organism* we can envisage how soft robots can radically change, and improve, our interactions with the natural environment and our management of natural resources.

2. Taking inspiration from Nature

A soft robotic organism will need to work in harmony with organisms in the environment. We can study these organisms and take inspiration from their life cycle in order to construct an environmentally sympathetic robotic life cycle. Natural organisms go through a continual cycle of birth, life and death. When they are living, organisms must operate in homeostasis both within their bodies and in interaction with the wider environment (Cannon 1932). For example, during daily living the organism may go through a cycle of resting, thinking, moving and eating. This cycle helps to maintain short-term homeostasis. When the organism dies it decays and fragments into elementary components which are, in turn, consumed by other organisms in the environment. This biological recycling maintains large scale and long-term environmental homeostasis.

If we are to move to fully sustainable robotics we must: 1. Work with the natural forces and conditions of environmental homeostasis, including biodegradation and resource re-use; and 2. Mimic per-organism homeostatic processes including feeding, metabolism and movement. Soft robotic technologies are highly suited to meet these challenges head on.

One important consideration is the scale of the robot. Biological organisms extend from micrometer scale bacteria to the 30 m/180 tonne blue whale. This range gives us the flexibility to design small, simple robots that operate collectively or to design larger complex robots that operate intelligently and independently. Given current soft robotic technologies, and especially the low level biomimetic technologies discussed here, a large number of small simple cooperating robots is more appropriate than one large complex robot.

We now consider how one might make a simple soft robot that could potentially operate safely, efficiently and with no negative impact within the natural environment. To do that we will consider both short-term and long-term homeostasis.

3. Soft robots as organisms

In order for a soft robotic organism to mimic its biological counterpart, and to maintain continuous homeostasis it needs to have two abilities: it must be able to feed itself and it must be able to move. Although feeding could be taken in its broadest sense as the absorption of energy, and hence could include conventional photovoltaics or direct electrical charging, we assume a more specific biomimetic view of feeding. Let us assume therefore that the robotic takes in the same biological material that its natural counterpart consumes and that it metabolises this material in its own 'stomach'. While we do not have the ready technology to exactly copy the breakdown and utilisation of organic materials in their chemical form as biological organisms do, we can mimic this effect using a microbial fuel cell (MFC), which has already been implemented in the field of robotics with the EcoBots (Ieropoulos et al. 2003). The MFC takes in organic material and live microbes (bacteria and algae) within the structure break this down and consume it. A by-product of this action is the release of electron-proton pairs. These charges are separated in the two-chamber microbial fuel cell, akin to a conventional H_2-O_2 fuel cell, and their movement through the cell circuit generates useable electrical energy. This energy can be stored in a capacitor for later use. It is has been shown that the microbial fuel cell is able to digest harmful algae (Gajda et al. 2015) and that microbes can also consume crude oil and even long-lived plastics such as poly(ethylene terephthalate) (PET), a common material for plastic drinks bottles (Yoshida et al. 2016). These capabilities mean that MFC-based robots have the potential for use in waste and pollution remediation activities.

The MFC provides a bio-mimetic, environmentally friendly energy source that, because it exploits the actions of naturally occurring microbes, encourages large-scale environmental homeostasis. Having satisfied the above stated requirement for a robot that can feed, we now need to satisfy the requirement for mobility. Biological organisms use movement to search for and gather food. Working towards a fully environmentally-integrated robot, the RowBot has been developed (Philamore et al. 2015), which differs from EcoBot in terms of design, material compliance and environment (Fig. 2a). RowBot mimics the movement of the water boatman *Hesperocorixa castanea* (Fig. 2b) and the feeding mechanism of the basking shark. It has a microbial fuel cell stomach and employs a soft robotic compliant mouth mechanism to control feeding and waste evacuation. When the RowBot is running low on energy it opens its front mouth and rear waste gate and rows through water to gather a fresh load of nutrient-rich water. It then waits for some hours for the nutrients to be consumed by the microbes in the MFC stomach. The resulting electrical energy is stored in a capacitor ready for use in operating the mouth and rowing mechanisms. The RowBot shows that the energy inequality $E_{metabolise} > E_{rowing} + E_{mouth\_operation}$ can be achieved, where $E_{metabolise}$ is the energy extracted from consumed organic material in the MFC stomach, E_{rowing} is the energy used in locomotion and $E_{mouth\_operation}$

is the energy used in opening and closing the soft mouth and waste gate. Other methods for extracting energy from organic chemicals for soft robotics include combustion of organics volatiles (Loepfe et al. 2015) and hybrid soft robots utilising cardiac muscles (Cvetkovic et al. 2015).

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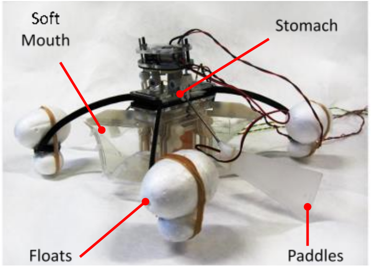
b 

Fig. 2 a.The RowBot environmental robot with soft mouth and MFC stomach (Philamore et al. 2015), **b**. the water boatman (James Lindsey, *Hesperocorixa castanea* from Commanster, Belgian High Ardennes, April 11, 2009 via Wikipedia, Creative Commons Attribution)

So far we have predominately considered how a robotic organism can maintain short-term, small-scale homeostasis through movement and feeding. Now let us consider the existence of the robot in the wider environment and the longer-term and larger-scale homeostasis of the environment itself. In this case the robot must have one crucial capability: it must be able to *decompose* and *biodegrade*. In this way there will be no build-up of persistent or toxic matter and environmental stability will be maintained.

It has recently been shown that soft robotics is particularly suited to the development of biodegradable and decomposing robots (Rossiter et al. 2016). Conventional rigid and electromechanical robots all face limitations with respect to their decomposition, due to complex component integration, and their degradation, due to the prevalence of non-biodegradable materials. In contrast, biodegradable soft robots can be fabricated from naturally occurring biopolymers such as agar, natural rubber (Tangboriboon et al. 2013) and gelatine/collagen (Chambers et al. 2014). These materials have been shown to act as electroactive polymer actuators (Fig. 3) and can therefore form the compliant body and 'artificial muscles' of a soft robotic organism. Combined with MFCs, they constitute the fundamental blueprint of a wide range of soft robots that live by feeding on freely available organic material, die when they come to the end of their life, and safely degrade to nothing in the environment. The materials that make up the robot are consumed by competing organisms with negligible overall impact. It has also been shown that MFCs themselves can be made biodegradable (Winfield et al. 2013)(Winfield et al. 2015). Such a low environmental impact means that we can also take radically different approaches to robot deployment. Instead of releasing and recovering a small number of non-biodegradable robots which must be recovered at the end of their productive lives, we can speculatively release hundreds, thousands or millions of biodegradable robots, safe in the knowledge that they will degrade to nothing in the environment.

Fig. 3 Electrical actuation of biodegradable gelatine. Frames 4s apart.

We have seen here that soft robots have the potential to revolutionise environmentally-interacting robotics. Like their biological equivalents they can live, die and degraded in harmony with the natural environment. The use of natural biopolymers also opens up radical new areas of robotics, including edible robots. What could be natural when you have a stomach pain to eat a robot which could then diagnose the problem, provide on-the-spot treatment and then be consumed by natural digestion within the body or in normal waste treatment once it leaves the body. As we have seen, eating, drinking, living, dying and decaying soft robots may assist in solving many of our most pressing natural and man-made problems.

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